Near Earth Optical Acquisition and Communication Exploration

Babak Sanii and Deborah Jackson

Brainstorm team members:
James Alexander
Abhijit Biswas
Juan Ceniceros
Hamid Hemmati
Deborah Jackson
Shinhak Lee
James Lesh
Jerry Ortiz
John Rothrock
John Sandusky
Babak Sanii
Keith Wilson &
Malcolm Wright

Introduction

Free space optical communications is widely viewed as a compliment to traditional radio frequency (RF) carriers at X-band and Ka-band on certain space missions where a high data rate downlink is required. Usually, the high data rate downlink is what drives the overall size of the RF telecom subsystems. It's optical counterpart offers higher data rates with lower volume, mass, and power consumption. But the current designs of deep space optical communication transceivers don't address the near Earth initial acquisition and communication needs that RF transponder designs do.

Performing initial acquisition and communication optically requires searching for and acquiring an uplink beacon from a large solid angle of space. Because of the rapidly changing trajectory near Earth, the downlink telescopes with their larger apertures and lower beam divergences are undesirable for initial acquisition communication because their small fields of view require a long scanning period to cover the full search volume. Lacking developed solutions to this specific challenge, optical communication system designers have to-date included a low-end, single string, RF telecommunication capability. However, the inclusion of such an RF system exacts a mass penalty of approximately 1.6 kg against the optical communication technology approach because a single RF transponder can be used to perform all of the above functions. This report addresses acquisition and communication in the first hour from separation by investigating whether an all-optical solution is possible, and then suggests possible technologies to perform the task.

Objective

The objective is to study all optical solutions to the initial acquisition problem, while looking for opportunities to match them with solutions already proposed for optical emergency command support. In the moments immediately after separation from the launch vehicle, a quick acquisition of the spacecraft is critical to establishing reliable navigation position predicts on the vehicle. Thereby the major performance requirements of an optical initial acquisition subsystem is to:

(1) Minimize the time required to search for and lock onto the uplink beacon (< 0.5 hour).

(2) Aid in the determination of the health, location, attitude and trajectory of the spacecraft.

(3) Identify an optical string of hardware that has no mass penalty compared with a functionally similar RF telecom subsystem.

The approach to meeting the objectives is a series of brainstorms with the members of the Jet Propulsion Lab Optical Communication Group, as well as cognizant individuals from relevant fields. Each brainstorming session raised new issues that were addressed and presented to the team by the next meeting. This activity was funded by TMOD.

Assumptions:

- Spacecraft (S/C) is attitude controlled.
- Trajectory is for a deep space mission with 8 to 14 hour initial pass length.
- Auto track capability once acquired at S-band.
- Maximum tracking rates:
  26 m antenna: 3^{o}/s
  34 m antenna: 0.8^{o}/s
  Octal telescope:
  - Azimuth: 20^{o}/s (acceleration $10^{o}/s^{2}$)
  - Elevation: 5^{o}/s (acceleration $5^{o}/s^{2}$)
- Typical data rates during initial acquisition: 4 kbps to 150 kbps

Background

Generic Launch Procedure

In the standard mission profile, the launch originates from Kennedy Space Center. Most trajectories move eastward, with the separation from the launch vehicle usually occurs over Africa. And the first acquisition is from the Canberra Deep Space Network (DSN), shortly after the satellite rises over the horizon in Australia. Errors in predicting the position occur due to a number of factors. The most prominent errors are caused by variations in the liftoff time, rocket performance, and atmospheric refraction at the time of the acquisition. The total position variance thus has the following contributions:

$$\sigma_{total}^2 = \sigma_{time-\mathrm{var}\,iation}^2 + \sigma_{rocket}^2 + \sigma_{atmosphere}^2$$

In current RF systems, there will also be frequency offset errors due to temperature variations in the temperature sensitive voltage controlled oscillator (VCO). An example of a launch time line, as well as spacecraft rise, range, angular rate and pass-duration are given in Appendix B.

Generic Nominal RF Initial Acquisition Procedure

Spacecraft

The spacecraft is usually housed in the nose cone of the launch vehicle during the launch. At a preprogrammed time after the lift-off, the spacecraft will separate from the vehicle. Shortly after the spacecraft separation, the solar cells are deployed and the attitude control subsystem orients the solar cells toward the sun to begin generating power. Next a designated spacecraft antenna will be pointed in the direction of the ground station to begin downlink transmission of a carrier signal. For missions employing nuclear power on the spacecraft, there is no need to charge up solar cells. The initial acquisition of the spacecraft carrier and data is generally done at this time. In some situations, the launch trajectory takes the spacecraft into Earth's shadow, where the solar cells would be unable to charge until it exits the shadow. Since this eclipse period may be up to an hour, a battery with sufficient charge to sustain operations for two hours is usually included on the spacecraft.

Ground Station

The details of each launch and initial acquisition procedure will vary according to the specific mission. In this discussion, we describe the Initial Acquisition Plan (IAP) developed for the Pathfinder mission. The procedures used on Pathfinder are probably generic to most of the Deep Space Missions, so a basic understanding of this plan gives one a feel for how other missions might be approached. In the best of all situations, the downlink signal is acquired from the spacecraft as it rises over the horizon. Using the initial predictions for the rise time and cross track position, the DSN sits and waits for the spacecraft to cross its path. This is known as "beam intercept mode", and is usually successful in acquiring the downlink signal. Typically, at S-band, the 3dB beam width is wide enough that the signal is acquired as soon as the spacecraft rises over the horizon. The narrower X-band 3 dB beam width increases the probability that the beam intercept position of the ground station misses the spacecraft as it rises. If the downlink signal is not observed within 30 seconds of the expected time, the acquisition antenna then performs circular scans about the predict position. It usually takes about a minute to complete a full circular scan.

In addition to scanning about the position uncertainty, one must also scan over the range of uncertainty in the downlink frequency. The frequency uncertainty is due both to Doppler shift and the temperature sensitivity of the VCO. The bandwidth of the best lock frequency of a typical X-band transponder on the spacecraft is only 200 Hz, while the Doppler shift induced by trajectory error may cause uncertainty of as much as 60 kHz. Ultimately, the narrow receiver bandwidth imposes a frequency scanning requirement on the search pattern, which is why the DSN receiver on the ground is designed to be tuned over $\pm$ 200 kHz about a center frequency that has usually been adjusted for the predicted variances. The uncertainty of the Doppler effect can shift the frequency away from the expected frequency so the receiver must be able to search or scan over a sufficiently large range to cover this uncertainty. This frequency scanning implies a minimum dwell time at each antenna position during any spatial scanning that occurs, while the frequency scan is completed. Once acquired, the receiver must be able to track far enough away from the nominal frequency to cover any changes in Doppler. The 26 m antenna receiver can currently track up to 230 kHz away from a center S-Band predicted frequency. Although the DSN cannot track all frequencies, the anticipated maximum Doppler shift tracking capabilities have been derived based on the maximum at S-Band and are given in Table 1 below.

TABLE 1. Maximum anticipated Doppler shift tracking capability at each carrier*

FREQUENCY	DOPPLER SHIFT
S-band	230 kHz
X-band	800 kHz
Ka-band	3.2 MHz
Optical	30 GHz

*Assumes current 26 m antenna frequency tracking range of 230 kHz @ S-band is adequate for initial acquisition function.

The spacecraft is usually continuously placing telemetry data onto the downlink. Once the ground station can acquire the downlink, this data can be used by the project to assess the health of the spacecraft. When appropriate, an uplink acquisition is attempted. Once the spacecraft acquires the uplink signal from the DSN, it typically switches from a one-way noncoherent mode to a two-way coherent mode. In the latter, the downlink signal is generated at a specific multiple of the uplink frequency. Once two-way coherence is established, further collection of spacecraft telemetry data (playback of launch data, verification of spacecraft health, etc.), the collection of two-way Doppler data for performing radiometric navigation, the uplink of any needed commands and ranging can commence. Once the navigation predicts are accurately determined from radiometric data, the initial acquisition phase of the mission is considered completed.

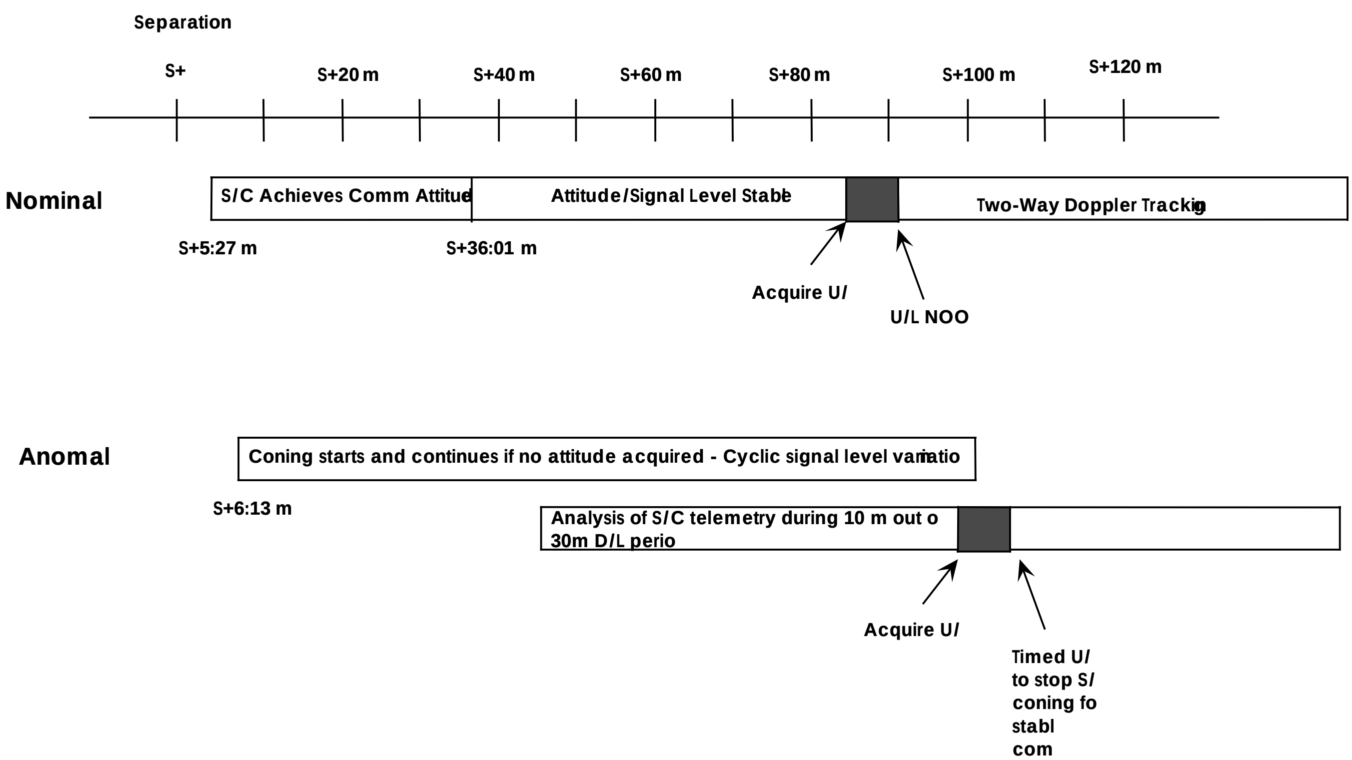


Figure 1. Mars Polar Lander timeline for initial acquisition.

Generic Anomalous RF Initial Acquisition Procedure

Spacecraft

The separation event initiates a command sequence on the spacecraft that eventually activates the solar cells, acquires attitude with the aid of star trackers or sun sensors, powers on the downlink transmit power amplifiers, and begins to transmit a signal for the DSN to acquire. After a successful separation event, if the spacecraft takes more than 10 minutes to acquire attitude using the star tracker, the command sequence attempts to use the sun-seeker to orient the vehicle instead. Once the sun is found, the spacecraft goes into a coning mode, pointing the boresight approximately 0.26 rad (15 degrees) off of the sun and completing a wobble at a rate of a few minutes per cycle. (NOTE: Even in the coning mode, the star tracker still continues to attempt to acquire a more complete orientation.)

Ground Station

The spacecraft attitude adjustments commencing shortly after separation cause fluctuations or loss of the downlink signal at the ground station. If conditions cause the coning mode to be utilized, the ground station will receive a periodic signal. In any case, the ground station attempts to acquire using the nominal acquisition procedure above. If it does not acquire within that time, it assumes the spacecraft is in a coning mode, and anticipates a periodic downlink. In addition, it increases the area of the circular scan. Other actions include using the acquisition aids, which are side mounted on the 26 meter acquisition antennas. These are lower gain antennas at S-band, which are designed with gains 18 dB lower than the 26 m antenna. One can also track the S-band downlink off of the launch vehicle's upper stage if its trajectory keeps it within a beam width of the spacecraft. The 34 m antenna is sometimes used as a backup antenna since the higher gain allows the spacecraft to often be tracked farther away from the antenna boresight, which gives the antenna an effectively larger active beam width, as long as the pointing errors are not too large. Because the 26 m tracking antennas do not support Ka-band band the higher gain 34 m antennas must be used for Ka-band support. But because the Ka-band has a narrower 3 dB beam width, Ka-band is not currently as practical for initial acquisitions.

Table 2.List of ground stations tracking hardware at each DSN site.

Carrier Frequency	26 m Antenna's 3 dB BW	Acquisition Aid* Antenna's 3 dB BW	34 m Antenna 3dB BW
S-band	0.36^o	4.0^o	0.24^o
X-band	none	2.4^o	0.08^o
Ka-band**	none	none	0.02^o
Optical (Not yet available)	none	0.3^o	$1.48\text{x}10^{-4}$ degs. (assumes 1 m Octal telescope)

- Acquisition aids located on 26 meter antenna.
- S-band band acquisition aid 18 dB down in gain from 26 m main antenna.
- X-band acquisition aid has a 36 dB gain.
- No 26 –m main antenna X-band capability exists.
- Currently Ka-band initial acquisition fails with no Ka-band acquisition aids.

Optical Comm Acquisition Requirements

With the translation from RF to optical frequencies, some of the physical parameters of the telecom link change significantly. This in turn leads to changes in the acquisition procedure to accommodate characteristics specific to optical links. A comparison of the major characteristics of the optical and RF links is summarized below. This is followed by a discussion of the ground rules for anticipated initial acquisition trajectory and how that changes the requirements on the optical telecom terminal.

Optical Comm Background

Antenna/aperture gain: First and foremost, the gain of the collection aperture is given by:

$$G = \frac{4\pi A}{\lambda^2}$$

For the same aperture area, **A**, one can see that the optical gain for 1 micron wavelength is a million times greater than the anticipated gain at Ka-band at 1 cm wavelength. This permits one to design tighter focusing optical links with much smaller apertures and is a leading advantage for going to optical links. Generally optical links are designed so that the larger link gains result in higher data rates. The drawback of tighter focusing optics is that it forces a tighter pointing requirement on both the spacecraft and the optical communications terminal.

Detection scheme: At optical frequencies, the rapid oscillation of the carrier makes the RF practice of phase detection unpractical. Therefore, all of the Earth to satellite and satellite to Earth optical communications schemes are based on the concept of direct detection after collection by a photon bucket. Optical detection is based on the measurement of currents created from the generation of electrons or electron hole pairs at the detector. At RF frequencies, the challenge is to measure the voltage created by eddy currents at the RF antenna.

Modulation scheme: At optical frequencies, atmospheric turbulence makes the RF practice of phase detection unpractical. Therefore, all of the Earth to satellite and satellite to Earth optical communications schemes are based on some form of amplitude modulation. Given direct detection, the modulation scheme is On/Off keying (OOK) or Pulse Position Modulation (PPM). In contrast, the RF transponders are based on Phase Key Shifting (PSK). Phase detection yields roughly a 20 dB improvement in detection sensitivity.

Doppler correction: The filter on the optical setup is typically going to be an interference filter with about a 1 nm linewidth ($\Delta\lambda \simeq 300$ GHz). This contrasts with the RF transponder which has a circuit filter with a 200 Hz bandwidth. The anticipated maximum Doppler shift is expected to fall well within the bandwidth of the optical filter, thereby making it unnecessary to scan the optical filter over frequencies in an effort to acquire the optical downlink signal. The drawback of this procedural simplification is that the wider filter bandwidth results in the detection of more relative background noise.

Weather sensitivity: The optical links are unable to sustain operation under heavy cloud cover. By comparison, the S-band carrier is impervious to rain; X-band and Ka-band show attenuation during rainy conditions, with Ka-band being the more sensitive of the two. The S-, X-, and Ka-band RF carriers propagate through cloud cover. Although the high data rate optical links can be operated in a store and forward mode in order to circumvent weather outages, the weather sensitivity may prove to be a serious detriment for the use of optical comm during the initial acquisition period.

A recent atmospheric visibility monitoring study (Piazzola), examining the visibility at two sites gives an indication of how the availability improves with more than one site. For example, perfectly cloudless sky conditions, as reported by the National Climatic Data Center, were observed at Edwards was roughly 27% of the time. In contrast, clear sky conditions at Tucson over the same period were observed 50% of the time. Using both sites, 61% of the time one or both sites had clear sky conditions. Since the sky does not have to be completely cloudless to complete the link this number for the availability of good optical link conditions is extremely conservative. It is also very site dependent, and is presented as a measure of the possible advantages of site diversity. More detailed site diversity statistics are expected from the Atmospheric Visibility Monitoring project.

Initial Acquisition Issues for Optical Comm

Weather: Currently, launches may be aborted due to high winds or other weather conditions at the launch site. The optical comm approach would also require one to insure clear weather and cloud conditions at the impacted ground receiver stations. A site diversity plan, based on Atmospheric Visibility Monitoring data, would be needed to minimize the probability that the launch would be scrubbed due to weather blockages at the ground stations.

Angular Search Volume: The angular search volume will be roughly the same as that for the RF telecom case. The difference is that the number of positions scanned during the search will be much larger due to the small field of view (FOV). However, the dwell time at each position will be reduced because there is no need to frequency scan.

Nominal Acquisition Procedures: The major difference between acquiring at optical frequencies as opposed to the RF frequencies is that in the RF, because of the implementation of omni-antennae, the "beam intercept mode" has the ground station fixed on a predict position waiting for the spacecraft downlink signal to cross its RF visibility path as it comes over the horizon. In the nominal optical mode, the groundstation points a beacon to the location of the spacecraft, the spacecraft acquires it and points back. Tight pointing requirements of the deep space telecommunication optics are susceptible to the possibility of mutual mispointing due to positional variances. Therefore, the ground station must correctly acquire the spacecraft and receive some form of feedback verifying its acquisition. Two approaches were proposed: (i) use of a corner-cube to provide a detectable reflection back to the ground once the spacecraft is in the beacon's path and (ii) optically acquire the spacecraft using a telescope.

Non-Nominal Acquisition Procedure: In both the RF and the optical cases the spacecraft goes into a coning mode. Now the spacecraft has not acquired the ground station within it's FOV making it difficult to either find the uplink beacon or to lock onto it. A solution might be to use a wide field of view imager to find the Earth beacon. Once found, the beacon can provide attitude information for spacecraft stabilization. After attitude stabilization, the optical pointing and tracking systems lock onto the uplink beacon and subsequently initiate a downlink.

Rapidly changing velocity and aspect angle rates: Near Earth, the velocity and aspect angle rates are significant, compared to deep space. Once acquired, the rate of angular change makes it difficult to keep the telescope centered on rapidly moving spacecraft without an automated tracking capability on the telescope. The greater challenge, however, is the ability of the optical comm subsystem on the spacecraft to maintain lock on the uplink beacon. This requires a combination of the spacecraft's attitude control adjustments and fine tuning at the optical comm terminal. A fast fine tuning mirror is used to make adjustments within the deep space communication system's field of view (about 8 mrad for current designs). This means that the spacecraft attitude control subsystem must compensate for any attitude changes above that, unless a coarse moving gimbal is used at considerable mass and power expense. The degree of achievable attitude control depends very much on the type of actuator's and attitude sensor's chosen for the mission. Two types of actuator's are typical for adjusting the attitude:

– reaction wheels
– reaction control jets or thrusters.

The reactions wheels are usually operated with continuous feedback to a fast control loop. Control using the thrusters is modulated by the overall inertia that the vehicle represents. The larger the inertia, the finer the control over the angular correction. However, since the propellant is a limited resource, there is a tendency to minimize the use of the thruster so that there is usually a "dead zone" of angular drift permitted from the assigned attitude setting before a correcting thruster is fired. On a mission like Cassini, reaction wheels permitted angular resolution as fine as 40 μrad (2.3 millidegrees) to be held for high resolution measurements. The rest of the time, thrusters are used to maintain a deadband of $\pm$ 17.5 mrad (1.0 deg). The other factor that limits how well the spacecraft attitude can be controlled is the capability of the attitude sensor. An Inertial Reference Unit (IRU) is one of the more sensitive methods of sensing attitude changes relative to some starting point. Current IRU technology can provide 0.25 μrad sensitivity. In contrast, a star tracker might provide 0.1 mrad attitude sensitivity normal to the boresight and 1 mrad attitude sensitivity along the boresight.

Ranges at rise: Sample ranges at rise over the Canberra ground station are represented in Figure 2 below. For deep space missions, the window for the initial ground track at Canberra can vary from as little as 5 hours (Cassini) to as much as 10 hours (Pathfinder). However, it is anticipated that the initial acquisition plan should provide a high probability that the spacecraft will be acquired within the first hour after rising.

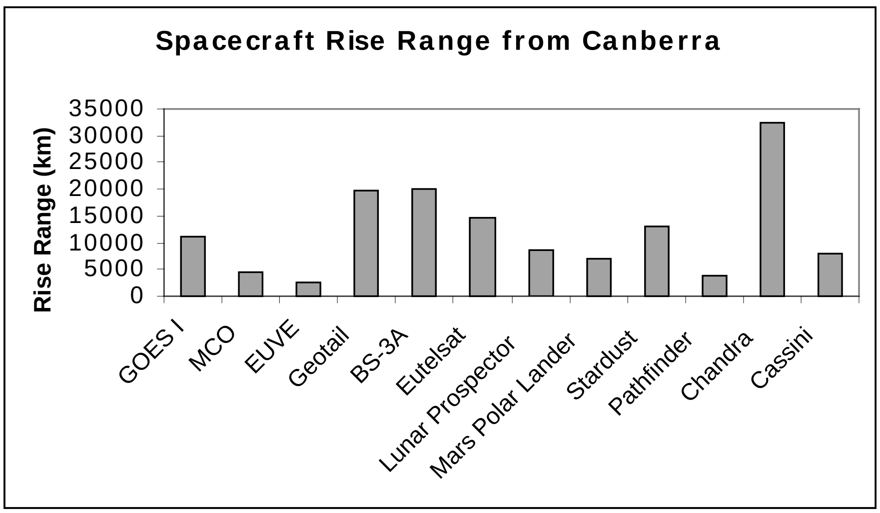


Figure 2. Rise ranges of various spacecraft from Canberra

The Concepts

The concepts that were discussed in the brainstorms may be roughly broken down into two categories: those aiding the process of acquisition and tracking, and those performing actual communication. Acquisition and tracking of the spacecraft from Earth is initially important for the purposes of determining launch vehicle success and generating spacecraft ephemeris information. When acquisition and tracking of the groundstation from the spacecraft is simultaneously performed, narrow beam optical communication may occur at high data rates.

However, some concepts were developed that would not require high accuracy acquisition and tracking from the spacecraft, but would enable optical communication. These concepts generally have greater power requirements, but provide a larger field of view for communication. They are, in essence, the optical equivalent of low-gain antennae.

Acquisition and Tracking aides

Acquisition and tracking has often been referred to as 80% of the optical communication challenge. The concept motivating most current designs is to have a communication terminal on the spacecraft that can transmit and receive light. On Earth, a beacon is transmitted to the spacecraft, and once the spacecraft "sees" it, it can lock onto it and return a beam to the same location. Both the beacon from Earth and the transmitted beam from the spacecraft can be extremely high data-rate communication channels. The challenges in the near Earth scenario are that the deep space spacecraft terminal will have an extremely narrow field of view in order to be able to point accurately once it is significantly further away. Also, to conserve power and reduce mass, it will not have a gimbal to coarsely point the terminal over a large range of motion, and must thus rely on the spacecraft's attitude control for coarse pointing, which may not be able to keep up with typical spacecraft angle variations in the near Earth scenario. Fine pointing is usually done with the aid of a fine steering mirror.

Three principal concepts were investigated, they were

(1) Spacecraft acquisition aides (Corner-Cubes or sun-illumination)
(2) Ground acquisition aides (alternative beacons)
(3) Requirements for angular tracking rates

Spacecraft Acquisition Aides: Corner Cubes

Corner Cube Retroreflectors (CCRs) consist of three orthogonal mirror planes, and have the property of reflecting light back in the same direction as it came, with a small planar displacement. Consequently, when illuminated along the path that it is being observed, the CCR is orders of magnitude brighter than a specular surface, which reflects the light back in wide range of directions.

By putting a small Corner-cube on the spacecraft, and illuminating it from Earth, one can verify that the ground-station has indeed acquired the spacecraft, even if the spacecraft has not acquired it. This is done by gathering the returned light and imaging its source. This allows the groundstation to stop its search pattern and wait for the spacecraft to acquire it. Furthermore it locates the spacecraft to verify launch vehicle success and allows ephemeris generation at much longer ranges than visual confirmation alone. Corner cubes have been launched on spacecraft in the past, and optical links have been performed with them. Links to the moon have also been performed, at a distance far larger than the near Earth scenario being considered (Wilson). Link analysis tables are included in appendix C, for reasonable ranges and corner-cube sizes. The spreadsheet developed to do the links can be used to determine the time it would take to scan a 4 degree cone (par with the current S-Band acquisition aid), as a function of spacecraft distance. A conservative link budget is also included that illustrates that it would be possible to scan a 4 degree cone within an hour and still expect to be able to detect a spacecraft with a trajectory similar to Pathfinder, accounting for the distance that the spacecraft would have traveled over the hour. Adjusting the divergence of the laser as a function of spacecraft range would significantly shorten the amount of time this scan would require.

Figure 2 assumes a 3cm-a-side corner-cube, and a dwell-time per scan equal to two round-trips of light between the ground-station and the spacecraft. There are a few issues that arise from this. Firstly, for a reasonable scan time, the spacecraft would have to be acquired within the first hour, even though the first pass will likely be at least 5 hours long. After the first hour, the acquisition benefit of the Corner-cubes diminishes greatly. This is because, in order to maintain a 3dB margin in the link, the transmitted beam from Earth must be kept to a smaller and smaller divergence. Consequently, this beam must scan a greater area, and must dwell at each area long enough for the signal to return (the dwell time is also a function of distance). This may be leveraged by using a more powerful laser; the pulsed laser investigated has a peak power of 32 megawatts. Once acquired, the divergence of the laser may be made smaller such that acquisition confirmation from the Corner-cube could be extended. In this model, a diffraction limited divergence would allow a link up to 670 thousand km.

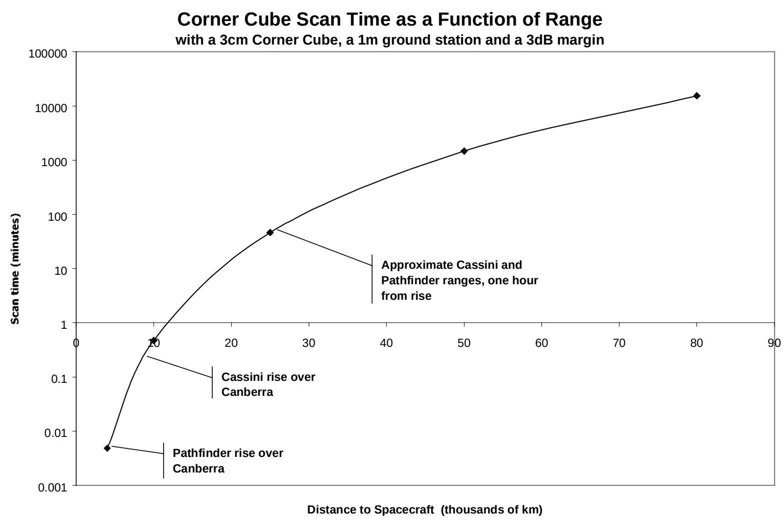


Figure 2. The expected 4 degree scan time as a function of spacecraft range.

Point ahead issues were also investigated. The agreement was that if the point ahead error would be larger than the field of view of the detector, a process of discrete movements would be implemented (instead of a continuous sweep). This process would entail transmitting the laser to the expected location of the spacecraft when the beam would arrive, and then waiting there, correcting only for sidereal motion. Then a discrete movement would take place to point to the next location, and repeating the process.

It must also be noted that more than one corner-cube may be desired, so as to increase the probability of success. Laser ranging can also be determined by way of the retroreflector on the spacecraft, by measuring the time between a transmitted and received pulse.

Spacecraft Acquisition Aides: Sun-illumination

It is also often possible to observe conventional spacecraft when sun-illuminated, but under much more limited circumstances. Because the light is of a similar spectral composition as the background of the sky during the day, background filtering is near to impossible, making daytime acquisition more difficult. Even at night there is the concern that the spacecraft will be, at least initially, in the shadow of the Earth. However, if the satellite is has a 90 degree phase angle of Sun illumination, is approximately the size of LandSat1 and at 2.5 Million km, it would be as bright as a 22nd magnitude star. 22nd magnitude is the expected limit of the current optical groundstation design. Thus this is a viable option for performing acquisition, but with restrictions on when one can perform it. This concept has been used by the Deep Space Network in the past; three optical trackers were mounted bore-sighted to the 34m antennas to verify satellite alignment for phased array experiments (Zingales).

Groundstation Acquisition Aides

By putting a large Corner-Cube near the ground-station, one may do the reverse. Once the spacecraft has located the reflection, it can track that point until the ground-station (which may still be searching for it) finds it. Large Corner-cubes must be used for this, however, and the greater required laser power on the spacecraft may invoke eye-safety concerns on Earth, which must be explored. A theoretical analysis illustrating range of this concept is included in appendix C. The possibility of using a high-power commercial spotlight to illuminate the spacecraft (so that it could in turn know where to point its return beam) was also explored. However, it was determined that this was not an applicable solution for deep-space spacecraft; its utility ranges were in the regime of low-Earth spacecraft, well below even the rise ranges we were considering.

These aides are not a complete answer to the Near Earth Optical Communication challenge. Indeed they are predominately to assist the ground-station in identifying the precise location of the spacecraft once visual spotting is no longer possible. Unless the corner cubes are modulated (at the expense of greater weight and complexity) no communication is performed, although bi-directional acquisition and tracking enables communication. It was also discussed that the corner-cubes may be ejected from the spacecraft after the Near Earth scenario, to conserve mass (the mass of a 3cm Corner-cube was estimated at about 100g).

Requirements for Angular Tracking Rates

Once correctly acquired, maintaining tracking is challenging, but doable. By looking at the plots of spacecraft aspect angular velocities when near Earth (figure 3) one sees that the angular velocity of Pathfinder (a more extreme case than Cassini) varies at a great rate initially, but very soon (in 9 minutes) comes to within a tenth of a degree per second. Speaking with spacecraft control experts, this velocity is easily compensated with reaction wheels, and compensated with a small error with thrusters. This is, of course, very dependent upon spacecraft configuration and mass. Once the slew is compensated for, the deadband of the spacecraft motion must be inspected. Typical deadbands are on the order of a degree to conserve fuel, but for situations requiring greater pointing accuracy a milliradian or two is also very doable. Ultimately spacecraft attitude knowledge plays an extremely large role in its control, and startrackers typically can report to within 1 mrad on their worst axis. Given the field of view of current optical communication terminals (7mrad), the challenge can be passed to its fine steering elements, which are designed to provide much greater pointing accuracy than needed for near Earth.

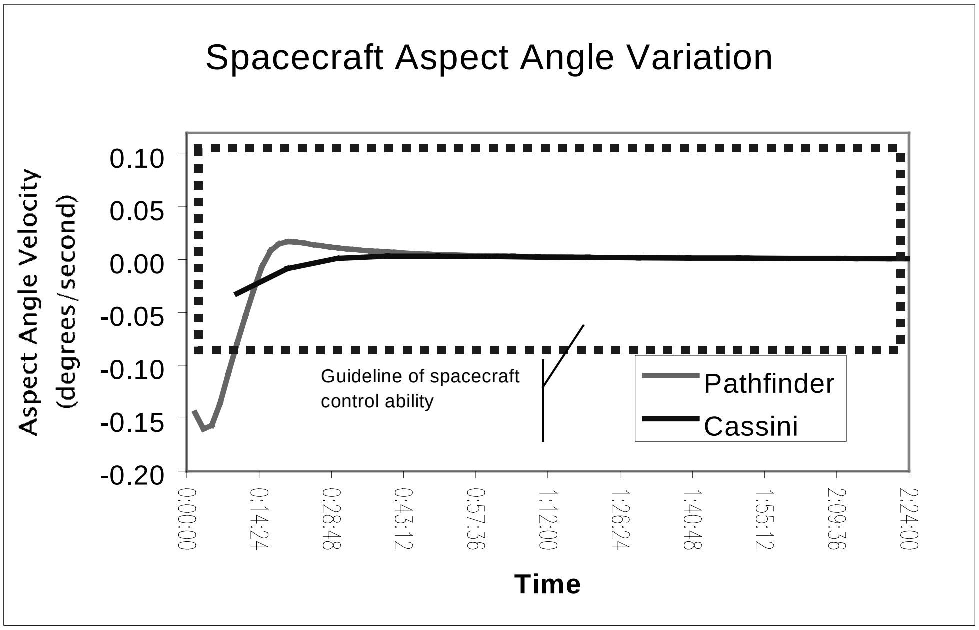


Figure 3. Spacecraft aspect angle rates as a function of time from separation.

Communication schemes and aides

Various communication schemes were discussed that would enable a link with or without completely accurate acquisition. These principal schemes discussed consisted of using

(1) the spacecraft's startracker for low-rate one-way communication

(2) a wide field of view transceiver

(3) a process combining the use of the star trackers and optical transceivers

(4) a low-capability RF system

Startracker for Low-Rate Uplink Communication

Spacecraft are currently being designed with star-trackers, to monitor and maintain three axis stability. In essence these devices are cameras and lenses, with elaborate software used to identify stars and determine spacecraft orientation based on them. These star-trackers have a variety of fields of view, ranging from 87 to 436 mrad (5 to 30 degrees), depending on the model used. To give some perspective on this, current designs for a deep space optical communication device have a field of view of about 8 mrad (0.5 degrees). Consequently, if there is a beam of light illuminating the spacecraft from the groundstation, the star-tracker will be able to find it far more easily than the communication terminal. This serves two purposes. Firstly, using the star-tracker and knowledge of its location with respect to the communication terminal, the error in pointing may be identified and steps may be taken to align the terminal to the groundstation. Secondly, extremely low data-rate commands may be sent to the spacecraft by modulating the beacon from Earth, and receiving the commands by observing the camera pixel values in the star-tracker. However, as these systems are not optimized for high-speed pixel readout, the data rates in question are on the order of Morse code. This may be enough, however, to uplink emergency commands to prevent catastrophic failure. A thorough analysis of optical emergency communication is not within the scope of this study, however, and has been addressed previously (Hemmati). A star tracker weighs between 1 and 6 kilograms, depending on the design and capabilities.

Wide Field of View Transceiver

This communication scheme, despite increasing the probability of success in acquisition, does not provide an alternate means of sending commands from the spacecraft to the ground-station. To have it do so would require a modification to the current design, or a new design altogether. This new component would have the capabilities of a star-tracker, with the added capacity to transmit a broader beam to Earth, and receive higher data-rates of communication. Various schemes were discussed, and sketches of their designs are included in appendix C. Most interestingly, a design of an optical communication terminal includes a small star-tracker attached to it, with an 8 degree field of view. Because it is attached, there are less concerns with spacecraft bending/twisting to confuse tracking problems, and it may be possible to reroute the same laser used for high gain communications to the broader field of view system. These schemes are truly the optical equivalent to the low-gain antenna, and require further investigation and design work. As for precedent, the Galileo Optical Experiment

(GOPEX) has demonstrated the use of a wide field of view detector to receive optical signals from Earth at a range of up to 6 million kilometers away (Wilson).

Process Combining the Use of the Star Trackers and Optical Transceivers

Assuming an optical communication terminal with a star-tracker attached, and a secondary larger-field-of-view startracker onboard the spacecraft, a tree of action was designed, and is presented in figure 4. It is written from the perspective of the spacecraft, independent of any instruction received from Earth.

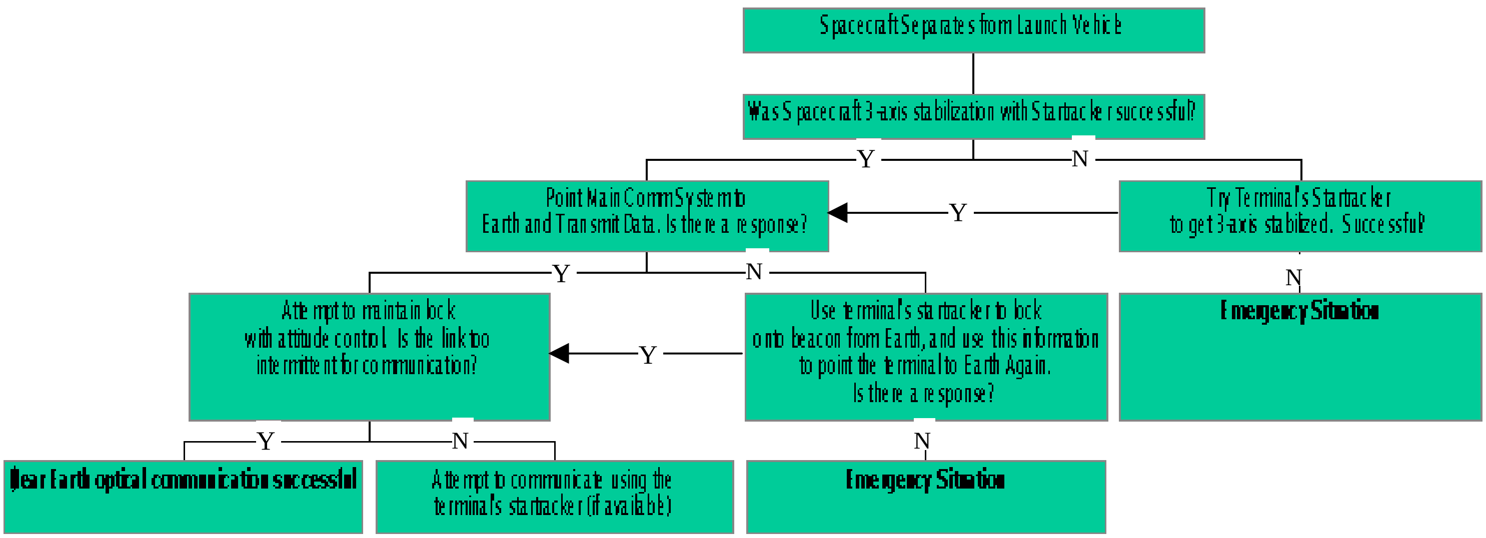


Figure 4. Process combining the use of star trackers and optical transceivers.

Another concept discussed was taking advantage of the high-data rate capability of optical communications to contain all the necessary data (spacecraft state of health and commands) in an extremely brief burst, which would be sent repetitively. This way, should the ground and spacecraft transceivers be aligned for only a small portion of the spacecraft pointing deadband, effective near Earth emergency could take place.

Concepts briefly explored included linking to the RF communication system on the launch vehicle for communication to Earth, visually tracking the spacecraft from another spacecraft/station, and using the GPS network for determining location.

Low Capability RF System

Finally, a low-capability RF low-gain antenna system was considered. Based on a design discussed for Team-X, this system weighed less than 1.6 kilograms (see Appendix A), and would perform all the necessary functions of near Earth communications. This design is, in fact, an excellent benchmark for the optical low-gain-antenna design. If it cannot outperform it on the basis of capability, cost, mass and complexity, the RF solution may well be the most desirable one.

Future Work

The three brainstorms and subsequent investigations identified three critical concepts to address the issue of near Earth acquisition and communication with a deep space optical communication terminal. The concepts that merit prioritized further investigation are

(1) a flexible optical communication platform.
(2) a spacecraft acquisition aid
(3) a ground-station acquisition aid

A flexible optical communication platform would serve as a communication tool for limited attitude control scenarios. It would consist of a large or variable field of view transceiver and could theoretically use the main communication system components for reduced mass. Furthermore it could serve as a redundant star-tracking system, an imager and an emergency communication tool. Investigations into the field of view requirements are needed, and further technology developments in flight qualified variable divergence control systems and optical path re-routing systems would be needed to create an efficient system. This concept merits further design and technology development, but could serve as a complete near Earth optical communication solution while providing other spacecraft redundancies.

The spacecraft acquisition aid study would be a comparison between using direct sun-lit observation of a spacecraft with placing a series of corner-cubes on the spacecraft. This would provide a greater likelihood of initial acquisition, as well as independent ephemeris generation and launch vehicle performance confirmation. If pursued, key design items would include availability, range limits and required ground-station support equipment. The number and sizes of retroreflectors would also have to be investigated.

The ground-station acquisition aid would consist of a wide-angle ground transmitted beacon. This would afford a larger orbital illuminated area, thus providing a greater likelihood that the spacecraft would acquire the groundstation quickly. A study illustrating an optical beacon divergence/power tradeoff as a function of required range would be required if this was to be pursued. A quantatative investigation on the time-saving benefits of this technique would also have to be included.

Conclusions

The spacecraft aspect angular rates of change on deep space launch trajectories were not as large as we had anticipated. After an initial few minutes of rapid changes, they quickly settled into a range where the spacecraft attitude control subsystem could compensate for the anticipated rates of change. The main challenge would be the situation where the spacecraft fails to acquire attitude, or cannot point the terminal to Earth because of other spacecraft requirements at that time.

With its narrow field of view, the telecom terminal cannot be expected to lock onto a periodically sweeping beacon for extended periods. Thus it becomes important to explore the use of wide field of view transmit/receive terminals that can track a sweeping uplink beacon and acquire without being directly pointed at Earth. Furthermore this flexible optical communication terminal could possibly perform as a redundant star-tracker and imager, as well as eliminate the fuel consumption that would have been needed for tight pointing near Earth.

This initial investigation, and hardware implementations such as GOPEX (Levine, Wilson), GOLD (Wilson), the optical telescope trackers on DSS-13 (Zingales), and spacecraft corner-cube links (Wilson), indicate that some of the optical near Earth acquisition and communication component technologies are mature and deployable. Others, such as a wide field of view beacon and a flexible optical communication platform require further development for near Earth optical communication to be successful.

References

Brown, W., "A Novel Nearly 4• steradian gimbal-less optical transmitter" ,*SPIE Proceedings, Vol 1866*, pp. 255-262, August, 1993.

Hemmati, H. Private communication.

Levine, B.M., Shaik, K.S., and yan, T.-Y., "Data Analysis for GOPEX Image Frames" , *The Telecommunications and Data Acquisition Progress Report 42-114, vol April-June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 213-229, August 15, 1993.

Null, G.W., Owen, W.M., and Synnott, S.P., "Systems Analysis for Ground-Based Optical Navigation" , *The Telecommunications and Data Acquisition Progress Report 42-111, vol. July-September 1992*, Jet Propulsion Laboratory, Pasadena, California, pp. 23-40, November 15, 1992.

Piazzolla, S., Sobin, S. and Amini, E., "Cloud Coverage Diversity Statistics for Optical Communications in the Southwestern United States" , JPL Report #_____, September 2000.

Reidel, J.Dl, Bhaskaran, S., Desai, D., Han, D., Kennedy, B., McElrath, T., Null, G.W., Ryne, M., Synnott, S.P., Wang, T.C., and Werner, R.A. "Using Autonomous Navigation for Interplanetary Missions: Mission Operations with *Deep Space-1* Autonav", *Space Ops 2000*, Toulouse France, CNES, June 19-23, 2000.

Reidel, J.Dl, Bhaskaran, S., Desai, D., Han, D., Kennedy, B., McElrath, T., Null, G.W., Ryne, M., Synnott, S.P., Wang, T.C., and Werner, R.A. ""Using Autonomous Navigation for Interplanetary Missions: The Validation of Deep Space-1 Autonav", *4th IAA International Conference on Low-Cost Planetary Missions*, May 2-5, 2000.

Wilson, K.E., and Lesh, J.R., "An Overview of the Galileo Optical Experiment (GOPEX)" , *The Telecommunications and Data Acquisition Progress Report 42-114, vol. April-June 1993*, Jet Propulsion Laboratory, Pasadena, California, pp. 192-204, August 15, 1993.

Wilson, "An Overview of the GOLD Experiment Between the ETS-VI Satellite and the Table Mountain Facility" , TDA Progress Report 42-124, February 15, 1996, pp. 8-19.

Wilson, K. E., P. R. Leatherman, R. Cleis, J. Spinhirne, and R. Q. Fugate, "Results of the Compensated Earth-Moon-Earth Retroreflector Laser Link (CEMERLL) Experiment," *TDA PR 42-131, July-September 1997*, pp. 1-13, November 15, 1997.

Yu, J, and Shao, M, "Galileo Optical Experiment (GOPEX) Optical Train: Design and Validation at the Table Mountain Facility" , TDA Progress Report 42-114, August 15, 1993, pp. 236-247.

Zingales, S. H., Private Communication.

APPENDIX A

RF Telecom Equipment List

TABLE A.1 Single String, Low End telecom design; supports Initial Acquisition function only

Description	No.	Mass (kg)	Comments
X-Up; X-down Spacecraft Transponding Modem (STM)	1	1.5	16 mW RF output power
TECOM Omni antenna	2	0.06	
TOTAL MASS		1.56	

TABLE A.2 Single- and dual-string X-band telecom, supports all telecom functions defined in the introduction

Description	#	Single String Mass (kg)	#	Dual String Mass (kg)	Comments
X-Up; X-down Spacecraft Transponding Modem (STM)	1	1.5	2	3.0	16 mW RF output power
TECOM Omni antenna	2	0.06	2	0.06	
5 W Solid State Power Amplifier (SSPA)	1	1.2	2	2.4	
X-band Medium gain patch antenna (MGA)	1	0.9	1	0.9	
X-band 1 m High Gain Antenna	1	1.3	1	1.3	
TOTAL MASS		4.96		7.66	

APPENDIX B

	Time (GMT)	Lapsed Time	Event/Description
1	18:45:51	00:00:00	LiftOff
2	18:46:54	00:01:03	SRM Burnout
3	18:50:15	00:04:24	MECO – Main Engine Cutoff
4	18:50:23	00:04:32	Stage I separation
5	18:50:28	00:04:37	Stage Ii Ignition
6	18:57:08	00:11:17	SECO – 1 – Stage II First Cutoff
7	19:25:02	00:39:11	Stage II Restart
8	19:25:23	00:39:32	SECO II – Stage II Second Cutoff
9	19:26:16	00:40:25	Stage II Separation
10	19:26:53	00:41:02	Stage III Ignition
11	19:28:21	00:42:30	TECO – Third Stage Cutoff
12	19:33:03	00:47:12	Yo –Yo Despin
13	19:33:08	00:47:17	Spacecraft Separation
14	19:34:19	00:48:28	S/C – Transmitter (SSPA) Power On
15	19:37:51	00:52:00	Start Solar Array Deploy Sequence
16	19:40:00	00:54:09	DSS-46: BOT – S-band Lock on the 3 rd Stage & X-band lock on S/C is possible although significant variation in signal strength is expected
17	19:40:00	00:54:09	DSS-45: BOT - X-band lock on S/C is possible although significant variation in signal strength is expected
18	19:42:35	00:56:44	Earliest Possible Time for S/C @ COMM ATTITUDE
19	19:46:06	01:00:15	Solar Array Deploy Sequence Completed
20	19:53:52	01:08:01	Start Unrestrain sequence (Moves solar array out of hook and places in position for initial acquisition
21	19:55:37	01:09:46	End unrestrain sequence
22	20:14:54	01:29:03	Latest possible time for S/C COMM
23	20:20:00	01:34:09	AOS + 5 MIN POLL (Time Approximate and depends on X-band lock on S/C)
23	21:05:00	02:19:09	DSS-45 Transmitter On (Time Approximate MCO ACE will coordinate with DSS-45)

GLOSSARY FOR SEQUENCE OF EVENTS

MECO	Main Engine Cutoff
I-II SEP	Stage 1/stage 2 separation
SI	Second stage ignition
SECO1	Second stage engine cutoff 1
SR	Second stage restart
SECO2	Second stage engine cutoff 2
II-III SEP	Stage 2/stage 3 separation
TI	Third stage ignition
TECO	Third stage engine cutoff
SEP	Spacecraft separation

Approximate spacecraft rise, set and range values of interest

Pathfinder
Range at rise: 4000km
Duration of pass: 10 hours
Range at set: 180000km
Maximum aspect variation rate: 2.8mrad/s (0.16 degrees/s)
Aspect variation rate 15 minutes from rise: 0.12 mrad/s (0.007 degrees/s)

Cassini
Range at rise: 8000km
Duration of pass: 5 hours
Range at set: 110000km
Maximum aspect variation rate: 0.5mrad (0.03 degrees/s)
Aspect variation rate 15 minutes from rise: 0.3mrad (0.02 degrees/s)

Cassini and Pathfinder are shown because they represent opposite edges of the spectrum with regard to most of these values.

Appendix C

A Corner-cube link analysis for pathfinder, as it rises.

<u>**Input**</u>		<u>**Output**</u>	
Wavelength (nm)	1064		
Laser Peak Pulse Power (W)	3.20E+07		
Initial Beam Width (mm)	1000		
Laser Divergence (mrad)	2.99E+01	Laser Footprint (m^2)	11254571927
Diffraction Limited Divergence (urad)	1.064	Laser Intensity at CCR (W/m^2)	0.001819705
Distance to CCR (m)	**4.00E+06**	Power striking CCR (W)	2.83664E-06
Air Transmission (%/100)	0.64	Power returning from CCR (W)	2.55298E-06
CCR side length (cm)	**3**	Return beam Footprint (m^2)	54333.70016
CCR area (m^2)	1.56E-03	Return beam Intensity (W/m^2)	3.00717E-11
CCR efficiency (%/100)	0.9	lux (lm/m^2)	2.0597E-08
CCR divergence (mrad)	0.07	**Gathered Power (W)**	9.98E-12
Return Optic Transmission	0.66		
Return Optic Size (m)	**1**	***Margin with current lab APDs (dB)***	***3.0***

<u>**Scanning**</u>		
Dwell time (s) (two R/Ts)	0.05	(two round-trips of light)
Cone to Scan (degrees)	**4**	(S-Band Acquisition Aid)
Scan Separation (mrad)	29.92427963	(initial divergence of beam out)
Scan Time (min)	**0.0048381**	
Scan Time (hours)	**8.063E-05**	

Distance (km)	**4000**	(Pathfinder rise)
Corner-Cube Side Length (cm)	**3**	
Groundstation size (m)	**1**	(Octal)
dB Margin with Current APDs	**3.0**	(Hammamatsu C5460)
Hours to scan a 4 degree cone	**0**	(par with S-Band Acquisition Aid)

A Corner-cube link analysis determining the farthest distance possible to scan within an hour, maintaining a 3db margin and a reasonable system. The range is farther than Pathfinder's range after an hour of flight.

Input		**Output**	
Wavelength (nm)	1064		
Laser Peak Pulse Power (W)	3.20E+07		
Initial Beam Width (mm)	1000		
Laser Divergence (mrad)	6.85E-01	Laser Footprint (m^2)	257626493.6
Diffraction Limited Divergence (urad)	1.064	Laser Intensity at CCR (W/m^2)	0.07949493
Distance to CCR (m)	**2.64E+07**	Power striking CCR (W)	0.00012392
Air Transmission (%/100)	0.64	Power returning from CCR (W)	0.000111528
CCR side length (cm)	**3**	Return beam Footprint (m^2)	2373079.442
CCR area (m^2)	1.56E-03	Return beam Intensity (W/m^2)	3.00783E-11
CCR efficiency (%/100)	0.9	lux (lm/m^2)	2.06016E-08
CCR divergence (mrad)	0.07	**Gathered Power (W)**	9.98E-12
Return Optic Transmission	0.66		
Return Optic Size (m)	**1**	***Margin with current lab APDs (dB)***	***3.0***

Scanning		
Dwell time (s) (two R/Ts)	0.35	(two round-trips of light)
Cone to Scan (degrees)	**4**	(S-Band Acquisition Aid)
Scan Separation (mrad)	0.685085873	(initial divergence of beam out)
Scan Time (min)	**61.003246**	
Scan Time (hours)	**1.0167208**	

Distance (km)	**26435**	(Pathfinder after over an hour)
Corner-Cube Side Length (cm)	**3**	
Groundstation size (m)	**1**	(Octal)
dB Margin with Current APDs	**3.0**	(Hammamatsu C5460)
Hours to scan a 4 degree cone	**1.0**	(par with S-Band Acquisition Aid)

Analysis of Using a Corner-cube on Earth

Assuming that we have a system capable of performing a link with an object at an extremely long distance, D_{far} away, the collected power would be:

$$\text{Collected power from far away} = P_o\left(\frac{\alpha_{atm}A_{telescope}}{\pi(D_{far}\tan\theta_{div})^2}\right)$$

Where α_{atm} is the atmospheric attenuation, P_o is the initial power out from the spacecraft, $A_{telescope}$ is the area of the ground telescope, D_{far} is the distance at which this link was possible (i.e. Mars) and θ_{div} is the divergence of the laser.

Conversely, if we were to perform a Corner-cube link at a much closer range, D_{close}, it would look like:

$$\text{Collected power from nearby Corner-cube} = P_o\left(\frac{\alpha_{atm}A_{CCR}}{\pi(D_{close}\tan\theta_{div})^2}\right)\left(\frac{\alpha_{atm}A_{ter\min al}}{\pi(D_{close}\tan\theta_{div})^2}\right)$$

Where A_{CCR} and $A_{terminal}$ are the area of the corner-cube on Earth and the area of the aperture of the optical terminal on the spacecraft, respectively.

Thus to collect the same power as we had from the far range link (which presumably was enough), we would equate the two equations and solve for D_{close}.

$$D_{close} = \left(\frac{\alpha_{atm}A_{CCR}A_{ter\min al}D_{far}{}^2}{A_{telescope}\pi\tan^2\theta_{div}}\right)^{1/4}$$

Making the following assumptions:

-The divergence of the reflection off the corner-cube is equal to that incidence upon it.
-The atmospheric effect on divergence is not included
-Atmospheric attenuation is symmetric
-The spacecraft has a similar detection mechanism as the groundstation

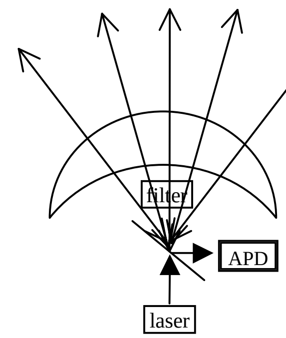
Using the following values

A_{CCR} = 1 m^2
$A_{telescope}$ = 0.79 m^2
D_{far} = 1AU = 1.5e8 km
α_{atm} = 0.67

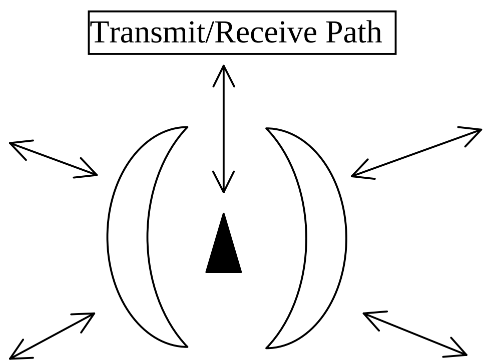
A table of maximum possible link ranges as a function of three principal terminal designs was created:

$A_{terminal}$ (cm)	$\bullet_{div}$ (urad)	D_{close} (km)
10	18	19,600
20	12	33,900
30	6	58,700

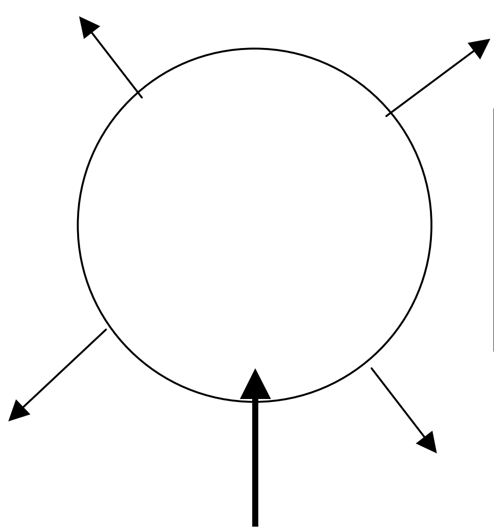
Concepts for very wide-field of view optical system



Fish-eye lens with a filter and transmit-receive components will allow a nearly 180 degree field of view.



Two lenses with a beam combining optic in the middle allows for an even greater field of view.



A partially reflecting sphere is pumped with a high-power laser that is free to bounce about inside it. At every bounce, a small portion of the beam escapes, ultimately creating an omni-directional transmitter.

Also see the paper by William Brown "A novel nearly 4-pi gimbal-less optical transmitter"